Free-Space Optical Data Bus for Spacecraft

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Abstract- **Our work applies optical backplane technology to the spacecraft data bus by implementing a free-space data bus suitable for the spacecraft environment. A free-space communications bus has a number of advantages, including ease of integration, ease of debugging, and lack of data harnesses. It is recognized that the free-space cavity design for an optical bus may not be suitable for all spacecraft architectures. The project had two components. The first was to model a possible packaging concept for a nanosatellite configuration proposed by NASA. In this model the energy transmission between the emitters and receivers was modeled to determine their performance parameters. To support the modeling effort, the bidirectional reflectance distribution function was measured on a number of materials and surface conditions including aluminum, sandblasted aluminum, and Delrin. In the second part of the project, we modeled and built technology demonstrators that implemented the MIL-STD-1553 and multi-drop RS-232 bus protocols using infrared (IR) emitters and receivers located in an optical cavity.**[†]

I. Introduction

Optical communication technology can be applied to spacecraft busses using either fiber optic cable interconnection or free-space connections. Fiber-optic cable data busses have been flown on a number of spacecraft. These spacecraft include the SAMPEX, MPTB, MAP, XTE, HST and PSE. These spacecraft implemented either MIL-STD-1773 or AS1773 bus protocols [1]. NASA has shown this technology to have a number of benefits that can also found in the proposed free-space communications bus. While a free-space optical data bus may be new to spacecraft, free-space optical data busses were first proposed by Gfeller who suggested a non-directional infrared (IR) wireless local area network using diffuse reflection in 1979 [2].

[†] This work was performed for NASA under the Cross-Enterprise Technology Development Program.

Free-space optical backplane technology is the focus of considerable research that has demonstrated numerous benefits [3, 4, and 5]. This technology uses optical communication between circuit boards to replace the interconnection typically provided by a backplane. The limited bandwidth of a normal electrical backplane is a bottleneck preventing development of fast systems. The skew, propagation delay, power consumption, and capacitive effect limit the backplane bandwidth. These factors keep the backplane bus operating at speeds much slower than the components. The transition to a free-space optical backplane eliminates many of these delays.

Standardization of the backplane interface simplifies the packaging and data handling of a system. This decreases the fixed engineering costs in developing new sub-systems or peripheral devices. This enables development of new and replacement sub-systems without extensive modification of existing hardware.

Nanosatellites, operating singly or in clusters, create the potential for a paradigm change in future spacecraft missions and designs. While a free-space communications bus may not be appropriate for a large spacecraft, they would be well suited for a nanosatellite. To implement this new concept, we first developed an IR intra-craft wireless bus capability using the MIL-STD-1553B and RS-232 protocols. Our goals were to maximize the reliable link margin in order to afford greater flexibility in receiver placement, which will ease technology insertion.

The project had two components. The first was to model one potential packaging configuration shown in Fig. 1. In this model the energy transmission between the emitters and receivers was modeled to determine the effect of their placement on system performance. In the second part of the project, we modeled and built two technology demonstrators that implemented the MIL-STD-1553 and multi-drop RS-232 bus protocols using IR emitters and receivers located in an optical cavity. One was a benchtop demonstrator of the technology and the other was integrated into a form factor similar to what a nanosatellite might have.

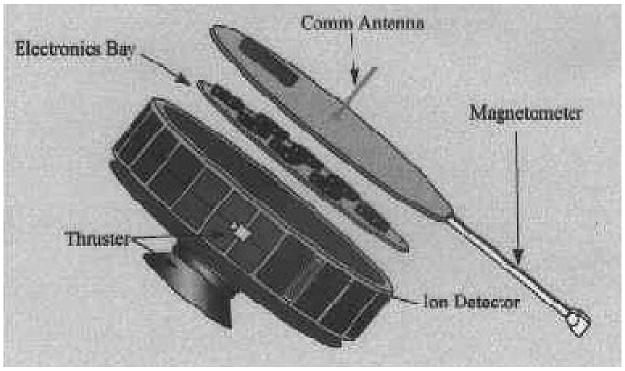

Fig. 1. Example of a small satellite designed by NASA/GSFC [6].

II. Free-Space Optical Data Bus Benefits

The replacement of a traditional wire bus with a free-space optical data bus has the potential to fundamentally change not only system design, but the sub-system design and integration costs. The electrical isolation provided by a free-space optical bus would simplify safe electrical integration leading to significant cost savings. Elimination of the data bus wiring harness and standardization of communications bus protocol would simplify testing and integration of spacecraft sub-systems and systems. The ability to reuse existing sub-system designs on a common spacecraft structure and infrastructure would be greatly facilitated.

Superficially, the replacement of copper wire harnesses with optical communications is merely evolutionary packaging development; however, further consideration shows that it will affect many areas of spacecraft design, test, and integration [1]. This technology has the potential to:

- Reduce integration time by eliminating much of the safety protocol involved with subsystem integration.
- Eliminate the weight of the data cable assemblies, improve reliability and reduce costs. Elimination of the fiber optic cable eliminates the connector, cable, cable routing issues and termination process as sources of failure. Not including design time, wiring harness assembly costs range from $20-40 per wire. This does not include the costs of testing and repairing of incorrect wiring and defective connectors. The problems in the wiring harness are usually identified and solved during the subsystem integration and are the source of many delays in this process. However, one report suggests that the volume needed for a free-space communications system will be larger than an equivalent fiber-optic system [7].
- Reduce electromagnetic interference (EMI).
- Simplify troubleshooting. Currently, troubleshooting is accomplished by using extender cards and probes to monitor system performance. Wireless optical communications frees up the need for these harnesses and extender cards, thereby facilitating measurement of circuit card performance. Even after integration, bus communications is easily monitored by an optical receiver system.
- Implement standardized network protocols. The potential to create and implement a standardized network protocol by implementing an optical interface would create an enormous opportunity. Standardization will facilitate reuse of existing designs and network testing of systems. Such tools could be used to test a system via an existing electronic network, allowing systems testing to be conducted without the hardware being located in the same room. Once the timing issues are addressed, it is possible that the spacecraft electronic hardware being tested could be physically located in different companies across the country. The key challenge in this will be in developing a method to accommodate the limited and uncertain bandwidth that a non-dedicated network provides.
- Eliminate fiber optic cable outgassing effects, and thermal and radiation degradation concerns. Without the fiber optic cable, it becomes unnecessary to accommodate for thermal cycling shrinkage and radiation degradation effects on the cable.

III. System Design Considerations

The long range goal of this research program was to begin to develop a wireless communications bus suitable for small spacecraft. It is recognized that the free-space cavity design may not be suitable for larger spacecraft or where suitable cavities are not available. However, there are several small spacecraft designs where a free-space communications bus would be suitable and preferable to the alternatives. The objective of the system design is to develop a common emitter/receiver subsystem that can be located throughout the spacecraft without the need for location-specific modifications.

The design and performance of the optical free-space bus should not be sensitive to its location, to the extent that sub-systems can be swapped out without system redesign thereby reducing the investment in spacecraft design. Each emitter and receiver subsystem should be redundant so that loss of a single component would have no effect on system performance. The command and data handling (C&DH) subsystem should have a bus monitoring capability. This monitoring circuit would provide a window on the performance of the communications bus during integration and test and after launch, the system would continue to monitor bus traffic, looking for change in system performance.

The most desirable communications protocol choice would utilize an existing protocol, such as Ethernet, which could be adapted to the IR physical layer. A commonly available protocol implementation could take advantage of commercially available cores for designing the digital portion of the transceiver. Simplifications of existing protocols may be possible because of the specific application and need to map protocol complexity to hardware complexity and power dissipation.

For example, the current Infrared Data Association (IrDA) Standard requires a significant amount of time to be spent in establishing the proper communications parameters before the data is actually sent. While this is necessary in an open system where communicating components can be added, moved and removed at any time, this time is wasted in a spacecraft where the environment is relatively well defined.

There are a number of network topologies that can be applied to a spacecraft bus protocol, including multiple point-to-point, star topology, ring topology and gateway. Protocols can include solicited and unsolicited messaging as well as master-slave and token passing. For single wavelength systems, acceptable protocols need to operate in a half duplex fashion, with only one node transmitting at one time.

If a popular commercial standard is used, the entire infrastructure of support becomes available, including bus analyzers, software drivers, and other test equipment. For a new non-standard protocol, the entire support infrastructure would have to be created for it to be used effectively, and the reliability of the new protocol would not be as well tested and understood as an established standard.

Three key characteristics of the protocol to be assessed are the data rate (or bandwidth), latency, and error detection and correction. Error detection and recovery are very critical in spacecraft, where radiation is expected to generate a few errors and the errors can result in loss of a spacecraft or irreplaceable data. Other evaluation factors include proper handling of collisions in the case of multiple masters, data latency in small packets, data transfer rates of large packets, and redundancy.

The ability of the communication protocols to handle error is critical in spacecraft optical bus systems. Errors attributed to single-event upsets (SEUs) were detected in the COBE spacecraft as it passed through the South Atlantic Anomaly [1]. The anomaly resulted in erroneous mirror movement; however, it had no effect on the success of the COBE mission. Many of the spacecraft with fiber-optic communications busses have implemented a MIL-STD-1773 bus with its dual cable "standby" redundancy capability.

An important parameter in selecting optical components is the effect of radiation on the performance of the infrared detector. On the TOPEX satellite, the failure of the thruster status circuit optocouplers was attributed to a change in the current transfer ratio [1]. The current transfer ratio is the ratio of optocoupler output current to the input current.

In a free-space communications bus, the components and design of the free-space cavity limit the potential bandwidth. The component performance, distance between components, and reflective characteristics of the free-space chamber interactively limit the available bandwidth. Without a fiber optic cable to conduct the light, the emitters will need to transmit more power which may negatively impact the power budget. To facilitate integration and testing, consideration needs to be given in the hardware or optical cavity design to reject ambient sunlight and 60-Herz light flicker.

The data bus rate drives the design of the optical space surrounding the optical components. In contrast with fiber-optic systems where fiber carries the light, free-space communications uses free-space or a diffuser material to distribute the light. If the optical chamber surrounding the transceivers were a nearly-perfect reflector, each transmitted pulse would create a received pulse much longer in time than the initial pulse due to internal reflections. The internal reflection of each pulse must decay below an intensity threshold before the next pulse can be sent. If the optical chamber is a blackbody, the issue of internal reflections becomes moot; however, this requires all of the transceiver assemblies to be located in line-of-sight of each other and may require more powerful emitters and more sensitive receivers. Other design alternatives include (a) using diffuser rods that scatter the light uniformly and (b) limiting the diffuse reflective surfaces to one region with the remainder of the system having optical blackbody characteristics.

The light path is not only dependent upon the reflective surfaces and diffusers; it is also dependent on the beamwidth of the emitter/receiver. By varying the beamwidth of the emitter and receiver elements and the focal length of the element lens, the system performance may be changed.

IV. Energy Transmission Analysis and Testing

Using a spacecraft design such as that shown in Fig. 1 the electronic packaging geometry shown in Fig. 7 was created. In this model, the plane of emitters and receivers were located on the bottom interior surface, and the reflector material was located above, on the top interior surface. The circuit cards would be mounted perpendicular to the reflector surface. The initial guidelines set the diameter at 30 cm and the height at 10 cm.

Fig. 2 includes the relevant parameters for the model. Here ψ is the emission angle of the source, and θr is the angle of reflection, as measured from the normal to the reflector surface. Each transceiver contains both an emitter and a detector, which allows a signal to be transmitted from and to any spatial location via the broadcast system. For the purposes of the model, the angle of incidence (θ_i) was constrained to be 0° for each emitter.

To calculate the irradiance received at each possible detector location, we calculated the flux from the emitter to the receiver, accounting for the BRDF of the reflecting surface. The BRDF is a surface property that describes the change in scattering intensity as a function the angles of incidnece and reflection.

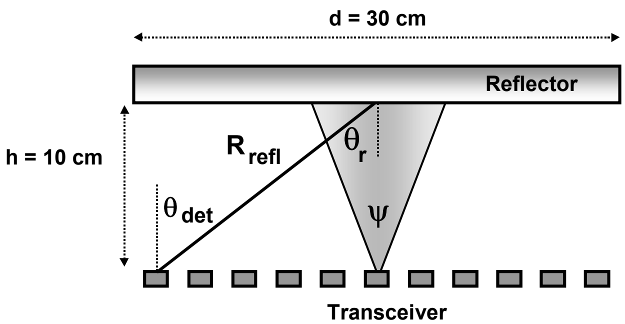

Fig. 2. Geometry for small satellite IR communications model.

To support the modeling effort, BRDFs were measured on a number of samples including aluminum, Delrin, sandblasted aluminum, and a solar cell. The results showed sandblasted aluminum as the most promising spacecraft material to be used as a reflector (Fig. 3). Sandblasted aluminum performed very close to a Lambertian surface, efficiently reflecting light over a wide angle. The ability to distribute light over a wide angle is crucial in minimizing the distance between the reflectors and transceivers thereby reducing the transceiver's power requirements.

From the model a number of observations were made. In order to achieve the maximum irradiance over a large range of reflection angles, the reflecting surface should have a high reflectivity and have Lambertian properties. For most materials there is a tradeoff between radiant intensity and emission angle for the source. Reducing the distance between the plane of transceivers and the reflecting material has two effects. It improves performance by shortening the path length but reduces performance by increasing the angle of reflection. Also, a receiver lens magnifies the effective area of the detector to increase sensitivity. Curving the reflector surface has the potential to increase the relative signal level received by outlying detectors. However, because the signal must travel a longer distance across the diameter of the satellite, the peak irradiance would decrease. Additional details of the BRDF measurements and the model may be found in [8].

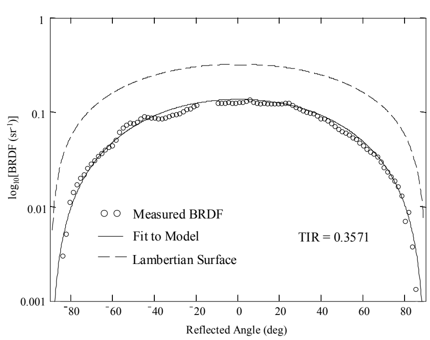

Fig. 3. BRDF measurements on sandblasted aluminum.

V. Technology Demonstrators

Fig. 2 was not the only geometry studied in this project. Two technology demonstrators were designed, fabricated and tested, one using a MIL-STD-1553 protocol and the other a multi-drop RS232 protocol.

The MIL-STD-1553 demonstrator was a bench top test of the suitability of COTS components for a free space IR bus implementation. It used IrDA transceivers and custom designed pulse reformatting electronics to interface with a 1553 controller. Because the IrDA transceiver is optimized to work with 125 ns pulse widths in its fast (FIR) mode, the reformatting, as graphically shown in Fig. 4, is necessary. Starting with the rising edge of the 1.5 µs start pulse, S0, the 1553 signal is sampled every 500 ns with a 125 ns IR pulse issued if the 1553 signal is high.

Fig. 5 illustrates the electronic functions needed to successfully interface with the 1553 controller. For verification of proper operation of the copper line drivers, a "wrap around" test is performed in hardware by comparing the states of the TX± and the RX± lines. A similar test could be done for the IR bus that would test proper operation of the optical transmitter and receiver elements. This was not done in this implementation, instead the TX± and RX± lines were wrapped around locally using the TX inhibit signal from the 1553 controller.

Reformatting the IrDA-received pulses to 1553 format consists of generating 500 ns pulses every time a 125 ns pulse is present. The total delay of formatting and reformatting is at worst 1 sample interval. Since in this implementation the transmit and receive clocks are not phase locked, they exhibit a relative drift in phase which must be considered for long block transfers.

Analysis showed that that these IrDA transceivers located 1 m apart would consume only 16% of the power consumed by a traditional 1553 copper bus transceiver. The power consumption can, of course, be further decreased by positioning the transceivers closer.

The approach used in the demonstrator prevented its use at large distances, because of the MIL-STD-1553 requirement that all master commands be acknowledged within 14 µs. The IrDA transceiver could not meet this specification at larger distances because of the automatic gain control response time of its receiver electronics. When transmitting, the IrDA receiver will see a large local IR signal and reduce its gain in response.

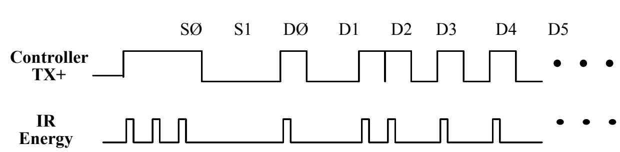

Fig. 4. IR Encoding of 1553 pulse train

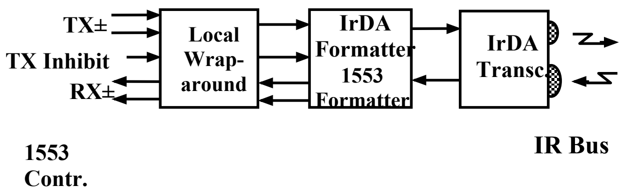

Fig. 5. 1553 to IR conversion functional blocks.

After transmission, the gain will recover too slowly for distant sources to meet the 14 μs requirement. Of course, a custom IR receiver design that circumvents this transmit-receive turnaround problem is possible.

To meet a system requirement for redundancy, a second IR transceiver could easily be used either in standby or concurrently.

The second technology demonstrator was a cubical spinner nanosatellite model (Fig. 6). Fig. 7 shows the interior details of the demonstrator. The cube is divided into 4 quarters with each quarter generating its own power from solar cells while spinning. One quarter contains a primitive C&DH that collects, upon command, a unique data item from each of the other cubes. The data items are then sent off-board by an IrDA transmitter to a compatible receiver interface for display on a PC.

Each cell has its own custom IR transceiver. In the center of the 4 quarters is a hollow rectangular region that acts as an optical chamber. IR LEDs and PIN diodes look into this chamber for bi-directional communication.

These cells use custom transceiver electronics for 115.2 K Baud communication with a UART (RS-232) controller to implement a multi-drop type of network. This type of bus was chosen over the MIL-STD-1553 bus in this implementation because the UART communications controller necessary to support it requires less power. The previous bench-top work had shown that the power requirements for the 1553-style bus were much greater and would require much larger solar cells. Since the focus of the second demonstrator was developing a low-power, nanosatellite system, the multi-drop RS-232 network was chosen.

VI. Conclusions

A free-space optical communications bus is proposed that has a number of potential benefits, particularly for small spacecraft. Beyond the obvious weight savings, there are potential cost and time savings in spacecraft design, manufacture, integration, and testing. To implement a free-space optical data bus, there are a number of system considerations in the selection of the hardware components and communications protocol.

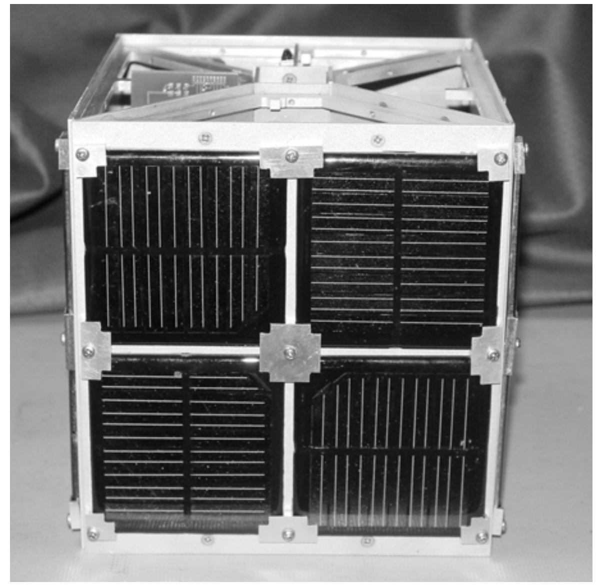

Fig. 6. A photograph of the technology demonstrator developed to test IR communications using a 115.2KB and UART (RS-232) "multi-drop" type of network.

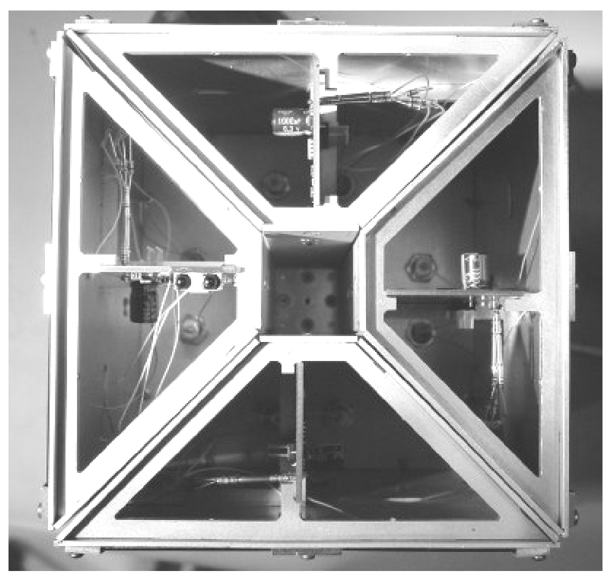

Fig. 7. A photograph showing the interior of the cube with the solar cells on the exterior surface. The model consisted of four independent cells, each with its own transceiver for communication and solar cell array for power. At the center is a free-space optical chamber that allowed communication to the cell on the left that transmitted the information to a laptop computer.

We developed two technology demonstrators. The first was a bench-top test of IrDA transceivers modified to support a MIL-STD-1553 bus. The testing and modeling showed significant power savings over a standard wired 1553 bus which was dependent on the distance between transceivers. The second technology demonstrator was a cube that contained 4 independent cells. Each cell had its own solar cells and used IR transceivers to form a UART (RS-232) "multi-drop" type of network. Using this network, each cell relayed a unique signal.

These two projects demonstrated the performance of two free-space optical protocols.

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